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College of Engineering
Ceramic Engineering Division

Multidisciplinary Research Activity
in the Materials Sciences with
Emphasis on Ceramic Materials

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Ceramic Engineering
Principal Investigator

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INTRODUCTION

The Ceramic Materials Research Program at the University of Washington was established June 1, 1963, under National Aeronautics and Space Administration Grant Number NsG-484. The principal purposes of the grant are to encourage multidisciplinary research upon the nature and properties of ceramic materials and to assist this institution in the development of an enduring research capability in ceramics and ceramic engineering. The funds are, therefore, used to make financial support available for research on ceramic materials conducted by members of the University faculty and to purchase such items of capital equipment as are deemed desirable for the implementation of the stated purposes.

The program, planned to study the effects of various energy environments upon ceramic materials, is divided into several broad research areas, namely; chemical, surface phenomena, solid state ceramics and processing. The research program is planned and coordinated by the Ceramic Materials Research Committee, the membership of which is appointed by the Dean of the Graduate School. The current membership includes James I. Mueller, Ceramic Engineering, Chairman and Principal Investigator; J. Gregory Dash, Physics; John L. Bjorkstam, Electrical Engineering; O. J. Whittemore, Jr., Ceramic Engineering; and Barry D. Lichter, Metallurgical Engineering. Administration of the program is coordinated by a board consisting of E. C. Lingafelter, Associate Dean of the Graduate School, Chairman; H. Myron Swarm, Acting Associate Dean, College of Engineering; D. A. Pifer, Director of the School of Mineral Engineering and James I. Mueller, Principal Investigator.

GENERAL PROGRAM REPORT

This is the ninth semiannual status report and covers the first half of the fifth year of operation under this grant. During the report period, a total of twenty-six projects were supervised by nineteen faculty members in six academic disciplines of the University. A table relating academic departments to research areas and to the number of individuals receiving support will be found in Appendix A.

The Ceramic Materials Research Seminar, a period devoted to discussions of concepts and research of interest to the program, met for a total of thirteen sessions during the past six months. The speakers included four graduate students, three University faculty members and six visitors. The latter included Dr. James C. Kemp, University of Oregon; Dr. M. Meshii, Northwestern University; Mr. S. W. Bradstreet, Technical Consultant; Dr. Arthur H. Heuer, Case Institute of Technology; Dr. S. M. Copley, Pratt & Whitney Aircraft; and Mr. Ferral Lytle, The Boeing Company.

The discussion group program continued as those faculty members and graduate students studying the solid state aspects of ceramic materials held bi-weekly meetings to discuss research areas of mutual interest and the chemical group continued their discussion of research on the zirconium-oxygen-carbon system. The program supported the attendance of eight faculty members to a total of three technical meetings at which four papers based upon work supported by the grant were presented. Papers published or presented resulting from work supported wholly or in part by the grant are listed with the individual status reports and in Appendix D.

Funds from the grant were used to supplement University support of a visiting professor during Summer Quarter. Dr. J. D. Mackenzie, Professor of Materials Science, Rensselaer Polytechnic Institute, Troy, New York, offered a four-week, three credit course during the "b" term of Summer Quarter entitled "Structures and Properties of Glass." A total of twenty-two from four different departments were enrolled.

Dr. William M. Ziniker was added to the Ceramic Engineering staff as Senior Research Associate to replace Dr. James D. Siegwarth who left the University to accept employment with the National Bureau of Standards. Dr. Ziniker received his doctorate in Physics from the University of Oregon in August 1967. Dr. Alan D. Miller, having completed the requirements for his doctorate in Ceramic Engineering in August 1967, was appointed a Research Assistant Professor in Ceramic Engineering in September 1967.

Two new projects were initiated during the report period, one under the supervision of Professor E. C. Lingafelter of the Department of Chemistry, and the other, under the guidance of Professor Colin Sandwith of Mechanical Engineering. Several items of capital equipment were received during the past six months. These include an Aminco surface area measurement apparatus, a Philips x-ray vacuum spectograph, including a goniometer, x-ray generator and controls.

Continuing our efforts to develop better communication between personnel in this program and individuals outside the University having similar research interests, a number of the latter were invited to attend the annual Autumn Program Review. In addition to the technical monitor from NASA, a total of sixteen visitors attended a briefing by research supervisors and visited research laboratories to exchange information with our personnel. A more detailed report is included as Appendix E. Where a similar effort last year resulted in an exchange of seminar speakers with Tektronix Corporation, this year's program has already made its effects manifest in that an exchange seminar has been arranged with the Battelle-Northwest Laboratories in Richland, Washington. Details of this will be given in the next progress report.

Initial arrangements have also been made to make an exchange with Rensselaer Polytechnic Institute. It is planned that a University of Washington faculty member will spend one-half month at RPI and that an RPI staff member will spend a similar period with the staff at the University of Washington. During this period, each would present a series of seminars relative to their work at their respective institutions and to spend consultation time with those members of the faculty and graduate students who have common research interests. In this manner, each of these two NASA supported institutions would be able to obtain more complete, firsthand knowledge of work being accomplished at the other university.

One of the purposes of this grant was to assist in increasing the number of graduate students working towards the doctorate in ceramics or ceramic engineering. The program is midway through the fifth year and a report of its effect upon these graduate enrollments is in order. Three individuals have completed their requirements for the Ph.D. in ceramic engineering to date. Whereas only two had entered the doctorate program during the first half year under the grant, there are twelve enrolled at the present time. A compilation of the total number of students partially or totally supported by the program since its inception is given by degree level and academic discipline in Appendix F.

RESEARCH STAFF

Faculty Supervisors:

J. L. Bjorkstam, Ph.D.
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R. L. Hawks, Ceramic Engineering
J. E. Kohler, Ceramic Engineering
R. L. Trantow, Metallurgical Engineering

Support Staff:

L. L. Miller, Office Assistant
D. W. Nevin, Engineering Assistant
V. V. Stringer, Secretary
L. A. Watson, Office Assistant
T. W. Woller, Machinist

STUDIES OF THE ZIRCONIUM-OXYGEN-CARBON SYSTEM

This system has been selected as the subject of a general study of the effects of the chemical environment upon ceramic materials. Several faculty members from various disciplines are participating in a coordinated study to obtain basic knowledge regarding this system.

GAS-SOLID EQUILIBRIUM

James I. Mueller
Professor, Ceramic Engineering

The composition and pressure of the gaseous phase(s) associated with the solid phases at various temperatures materially affects the equilibrium of a system. It is the purpose of this research to study the effects of these variables upon the Zr-O-C system.

Thermochemical Study of Zirconium Oxy-Carbide

A. D. Miller
Predoctoral Associate, Ceramic Engineering (June 16 to September 11)
Ph.D. Thesis Research

The initial portion of this project was completed during the reporting period with the following results.

The electronic band structures of a series of compositions corresponding to oxygen solution in the ZrC lattice were calculated using a modified tight-binding approach. The parameters necessary for the calculation were estimated from known values for similar materials. The band structures indicate that compositions with up to 50 percent oxygen substitution for carbon in the lattice remain metallic conductors. A calculation of the relative cohesive energy as a function of composition shows a minimum near 35 percent oxygen substitution. This behavior supports the presence of a ternary compound in the system.

An experimental study of the oxidation of ZrC was conducted with oxygen partial pressures between 10^{-6} atmospheres and 10^{-18} atmospheres and at temperatures between 1100°C and 1550°C. Two carbon monoxide pressures were used, one atmosphere and 0.033 atmospheres. The study did not yield any information as to the existence of the compound Zr₂CO. The results did, however, indicate very low solubilities of carbon in ZrO₂ and limited, if any, oxygen solubility in ZrC under these conditions.

Alan D. Miller received a Ph.D. in Ceramic Engineering, December 1967. Thesis title: "Electronic Band Structure and Oxygen Potential in the Zr-C-O System."

Studies of the Zirconium Dioxide-Carbon Reaction

S. K. Sarkar

Predoctoral Associate, Ceramic Engineering (June 16 to September 30)

Ph.D. Thesis Research

Previous work has indicated the evidence of a condensed phase, tentatively identified as $\text{ZrO}_{0.5}\text{C}_{0.5}$. The purpose of the continuing study is: (1) to obtain additional information upon the nature of the reactions involved, and (2), to make initial characterization of the material.

Studies to determine the initial requirements of the reaction indicate that, in a carbon tube furnace under 10^{-4} Torr vacuum, none of the proposed ternary phase is produced at temperatures less than 1500°C . A face-centered cubic phase other than ZrC has been identified at reaction temperatures between 1500°C and 1900°C . Work with the high temperature x-ray furnace using either a tantalum or a carbonized tantalum sample holder-resistance elements has resulted in the formation of a tantalum zirconate. Attempts have been made to determine the effects of lower vacuum or higher carbon content in the initial mixture on the formation of zirconium oxy-carbide. When tantalum or carbonized tantalum was used as a heating element and a much lower vacuum maintained in the system, the heating element burned out at 1800°C after one or two hours, so the study could not be continued. When carbon content in the mixture was increased, only ZrC was found to be formed at 1800°C and 10^{-5} Torr.

Some work has been done using different CO pressures in the graphite tube furnace. The lattice parameter was found to be $4.673 \pm .002$ A at different CO pressures. Some of the oxy-carbide so formed has been mixed with additional amounts of carbon and heated to 1800°C for three to four hours in the carbon heating element furnace. No change in the lattice parameter of the oxy-carbide was observed. Repeated efforts have been made, and are continuing, to study the effect of CO pressure on the kinetics of oxy-carbide formation. No definite trend has yet been found. The results obtained are quite random relative to the amount of oxy-carbide for a given time, temperature and initial composition of the mixture.

Influence of Oxygen Activity on the Structure of Zirconium Oxide

K. M. Nair

Predoctoral Associate, Ceramic Engineering (June 16 to December 15)

Ph.D. Thesis Research

The purpose of this study is the determination of the effects of low oxygen partial pressure at high temperature upon the stability of ZrO_2 . It is planned to study the possible existence of lower oxides of zirconium, their dependence upon oxygen activity and temperature, and the influence of the formation of such an oxide upon the formation of a ternary compound in the Zr-O-C system.

No stable oxides of zirconium lower than ZrO_2 have been observed in the equilibrium study of Zr-O systems for temperatures ranging between 700°C and 1600°C and oxygen partial pressures of range $\log \text{ oxygen pressure} = 10^{-14}$ and $\log \text{ oxygen pressure} = 10^{-2}$. It has been observed, however, that the color of " ZrO_2 " varied from black through shades of gray to white with increasing oxygen pressures. These "black oxides" changed to a white color when heated in air or oxygen. Precise study of diffraction line intensities and d-spacings at higher angles of the x-ray powder diffraction patterns have not shown any measureable changes with variation of oxygen partial pressure. Non-equilibrium study of Zr-O systems has given an oxide whose composition tentatively has been identified as " ZrO ." The ZnS structure of this material has a lattice parameter (a) equal to 3.8956\AA and, if unstable, will disproportionate as $2\text{"ZrO"} \rightarrow \text{ZrO}_2 + \text{"Zr"}^{\circ}$.

Thermodynamic calculations are underway to relate the activity of this finely dispersed " Zr " in ZrO_2 lattice which, hopefully, will lead to an explanation for the color of the so-called defect zirconia.

BONDING IN INTERSTITIAL COMPOUNDS

Alan D. Miller

Research Assistant Professor, Ceramic Engineering

A better understanding of electronic bonding in interstitial compounds is sought by this study.

Ultra-soft X-ray Emission Studies

James W. Rue

Research Assistant, Ceramic Engineering (September 16 to December 15)

M.S. Thesis Research

The purpose of the study is to provide experimental data concerning electronic energies in the zirconium-carbon-oxygen compositions whose band structures were previously estimated. This data will be generated by observing the ultra-soft x-ray emission spectra of carbon, oxygen and zirconium as emitted from compositions under consideration.

A vacuum x-ray spectrograph has been procured and the necessary modifications are being carried out. The windowless gas-type x-ray tube necessary for excitation is being designed and will be fabricated in our own shops. Concurrently, extensive research into the literature is being carried out.

SOLID-SOLID EQUILIBRIUM

N. W. Gregory
Professor, Department of Chemistry

A thermodynamic and kinetic study of chemical reactions in oxide-carbide-graphite systems.

Effusion Study of Graphite, Metal Oxide and Metal Carbide Systems

Juey Hong Rai
Research Assistant, Chemistry (June 16 to December 15)
Ph.D. Thesis Research

This is a study of steady state pressures generated in effusion cells by the interaction of metal oxides with graphite and by the interaction of metal oxides and metal carbides. It is hoped that this information will be of value in characterizing the composition and thermodynamic properties of the solid phases produced and/or the kinetic properties of the reactions which occur.

For the past six months work has centered mainly on the $\text{MgO} + \text{C}$, $\text{ZrO}_2 + \text{C}$ and $\text{MgO} + \text{ZrC}$ reactions. The $\text{MgO} + \text{C}$ reaction does not proceed rapidly enough to maintain the total pressure of Mg and CO in the reactants and products. CaF_2 is observed to have a catalytic effect; 5% CaF_2 in the pelletized equimolar mixture of MgO and graphite raises the total pressure by a factor of about five but values are still nearly a factor of ten less than the predicted equilibrium pressures. The early experimental results of Hollahan on the ZrO_2 -graphite reaction have been verified in new experiments. Addition of small amounts of CaF_2 does not change the CO steady state effusion pressures in this system. MgO is observed to react with ZrC ; Mg(g) and CO(g) are produced with effusion pressures in the measurable range in the vicinity of 1500°K . Again the total pressures developed in effusion cells are not as high as expected from thermodynamic properties of ZrC , but are closer (within a factor of about ten) than obtained in the ZrO_2 - C reaction.

Considerably more work is needed to verify and extend the results of these preliminary studies of the reaction between MgO and ZrC . The effect of different starting compositions of the ZrC phase will be of particular interest. Comparison of steady state pressures developed by interaction of MgO with the ZrC phase produced in previous effusion cell ZrO_2 -graphite reactions with that of ZrC phases prepared and characterized by other methods may provide a basis for conclusions about the similarity of these phases. It is hoped that ZrC phases of varying oxygen content and of varying Zr/C composition can be intercompared in this way.

CALORIMETRIC INVESTIGATION OF CERAMIC AND RELATED MATERIALS

Barry D. Lichter
Associate Professor, Metallurgical Engineering

The objectives are the construction of a high-temperature diphenyl-ether drop calorimeter and the study of heat capacity and heats of transformation of ceramic and related materials.

High-Temperature Drop Calorimetry

Hugo W. Schimmelbusch
Research Assistant, Metallurgical Engineering (June 16 to December 15)
M.S. Thesis Research

The construction of the calorimeter has been completed. The calorimeter consists of the following: drop mechanism, vertical high temperature tube furnace, upper and lower gates, calorimeter vessel-fin assembly, vacuum-inert gas valving system, sample weigh equipment, constant temperature bath, furnace control and sample temperature measuring equipment, and inert gas purifying train.

Calorimetric investigation of non-stoichiometric Zrc has been initiated. One of the results will be to obtain the heat capacity as a function of composition at various temperatures and to obtain information on its defect structure.

THERMODYNAMICS OF TERNARY CERAMIC PHASE DIAGRAMS

Gerald W. Toop
Assistant Professor, Metallurgical Engineering

The object of this investigation is to attempt to predict phase boundaries in ternary phase diagrams using the thermodynamic properties of the binary systems.

Ternary Ceramic Phase Diagrams

Dong Nyung Lee
Research Assistant, Metallurgical Engineering
M.S. Thesis Research

This work applied a method of calculation to ternary systems involving refractory metal oxides and carbides for which binary thermodynamic data was available. It was found that a promising way of displaying and analyzing the ternary data was to assemble a three-dimensional model of the ternary integral molar free energy of mixing surface. The phase boundaries could then be determined by applying a tangent plane to the model.

Further development of the theory showed that two of the three terms in the regular solution equation, used in the calculations, became general and rigorous near each pure component in any ternary system. This indicated that the method should give exceptional results in ternary systems in which one of the components was present as a major constituent.

The work in this area has been terminated due to Professor Toop's resignation from the faculty.

Dong Nyung Lee received an M.S. in Metallurgical Engineering, December 1967. Thesis title: "Prediction of Isothermal Ternary Phase Diagrams Using Binary Thermodynamic Data."

ZIRCONIUM OXIDATION

Thomas F. Archbold
Assistant Professor

This research project is investigating the characteristics and mechanisms of the initial stages of oxidation of zirconium metal. The oxide crystal structure and metal-oxide orientation relationships are to be determined as a function of oxygen partial pressure and temperature.

Zirconium Oxidation

L. P. Srivastava
Predoctoral Associate, Metallurgical Engineering (June 16 to December 15)
Ph.D. Thesis Research

The kinetics of zirconium oxidation and the identification of oxide structures are being investigated. The use of electron diffraction for the relatively difficult structure determinations and related structural characteristics was postponed early in 1967 in order that a comprehensive kinetic study could proceed. All of the actual oxidation runs have been performed for exposure times less than five minutes and at various temperatures and oxygen partial pressures. The present data indicate that, for times less than two minutes, the oxidation is parabolic with the diffusion of oxygen ions through the oxide layer being the rate-controlling factor. Also, the activation energy for the process, approximately 80 Kcal/mol, is not a function of the oxygen partial pressure. All data indicate that the oxidation mechanism changes after various exposure times depending upon the temperature. The kinetics information is now nearly complete, and the picture should be fairly complete as soon as the structural work has been accomplished.

SOLID STATE CERAMICS

The bulk properties of some ceramic materials are of prime importance and these are, for the most part, dependent upon structural considerations. The purpose of this research is to relate the nature of crystalline ceramics with appropriate properties.

DOMAIN DYNAMICS IN ISOMORPHOUS FERROELECTRICS

John L. Bjorkstam
Professor, Electrical Engineering

The objective of this investigation is to develop a microscopic model which explains essential features of the polarization reversal process in hydrogen bonded ferroelectrics of the KH_2PO_4 class.

Ferroelectric Domains and Domain Motion in KH_2PO_4 and DK_2PO_4

Richard E. Oettel
Predoctoral Associate, Electrical Engineering (June 16 to December 15)
Ph.D. Thesis Research

Significant results have been obtained on the temperature and field dependence of domain velocities for deuterated, partially deuterated, and non-deuterated samples of KH_2PO_4 . These measurements are continuing. The cooling apparatus has been modified to provide sample viewing and photography at higher magnification using a polarizing microscope. This was necessary in order to obtain data at low values of applied field for which total domain motion is small.

In addition to contributions in understanding the basic microscopic crystal properties which limit the switching rate of ferroelectrics, our research is concerned with the general problem of domain formation and polarization reversal in ferroelectrics. Many of the proposed uses for ferroelectrics depend upon these properties.

A paper entitled "180° Domain Formation in Ferroelectrics with Shorted Electrodes" by John L. Bjorkstam and Richard E. Oettel was published in the Physical Review, 159(2), pp. 427-430, 10 July 1967.

A paper entitled "Optical Evidence that the Low-Temperature Phase of Rochelle Salt is Antipolar" by Richard E. Oettel and John L. Bjorkstam was published in the Bulletin of the American Physical Society, 12(6), p.902, 1967.

STUDIES ON GASH

Edward C. Lingafelter
Professor, Department of Chemistry

Louis P. Torre
Research Assistant, Department of Chemistry (September 16 to December 15)
Ph.D. Thesis Research

It is the purpose of this program to investigate the mechanism of ferroelectricity in Guanadinium Chromium Sulfate Hexahydrate (GCrSH) and its Aluminum (GASH) isomorph by means of x-ray crystallography.

Crystals of both GASH and GCrSH have been grown under various conditions in an attempt to obtain thick crystals. Two crystals of GCrSH have been cut to a size and shape suitable for x-ray work by means of a "solvent saw." An electrical circuit which is appropriate for displaying hysteresis loops of very small (approx. .3x.3x.3 mm) crystals of GCrSH and GASH on an oscilloscope has been designed and assembled. It is currently being used to obtain hysteresis loops of much larger crystals in order to become familiar with their behavior. Solutions of GASH in heavy water have been prepared from which large crystals of deuterated GASH will be grown for use by Professor Bjorkstam in NMR studies.

It is planned to study the hysteresis loop of the specific crystal of GCrSH which will be used in the x-ray work. This crystal will then be poled with a d.c. voltage large enough to ensure saturation. The crystal structures of the crystal poled in opposite directions will be determined. The effect of exposing the crystal to x-rays will also be studied by observing the hysteresis loops.

PHASE TOPOGRAPHY

Jerry E. Turnbaugh
Assistant Professor, Ceramic Engineering

Selected microstructural features common to ceramics are being studied in terms of the variables leading to their development.

Phase Topography

Pei Sung
Predoctoral Associate, Ceramic Engineering (June 16 to August 31)
Ph.D. Thesis Research

The purpose of the present work is to measure the equilibrium solubility of Helium in UO_2 and to study the growth of Helium bubbles under conditions of supersaturation.

Helium saturation solubility and diffusivity in $\text{UO}_{2.015}$ was measured over the pressure-temperature range of 700 to 1300 psi and 1200 to 1500°C. The saturation solubility increased with increasing pressure and temperature according to the predicted relationship for stoichiometric UO_2 and agreed in magnitude to within a factor of two.

$$\ln \frac{\frac{N_i}{N}}{1 - \frac{N_i}{N}} = -\ln \frac{(2m)^{\frac{3}{2}} k^{\frac{5}{2}} \theta^3}{Ph^3 T^{\frac{1}{2}}} - \frac{W}{kT} + 4$$

Here m is the mass of helium atom, θ is the Debye temperature of UO_2 , P is pressure, T is temperature, W is the heat of solution, K is Boltzmann's constant, and h is Planck's constant. The observed heat of solution was approximately 30 Kcal/mol as compared to a calculated He strain energy of 5 Kcal/mol. The diffusivity could be described by the equation: $D = 5 \times 10^{-12} \exp(-12,700/RT)$. This low activation energy was felt to reflect He diffusion which was unhampered by defect clustering. Increasing pressure increased the diffusivity by a greater factor. The experimental He concentration vs. time curves of this investigation followed the spherical particle diffusion equations.

A paper entitled "Calculation of the Temperature-Dependent Shear Modulus of UO_2 " by J. E. Turnbaugh and Pei Sung has been accepted for publication in the Journal of Nuclear Materials.

A paper entitled "Calculation of Diffusivity and Solubility with Error Analysis for Diffusion in a Sphere" by J. E. Turnbaugh and Pei Sung has been accepted for publication in the Journal of Applied Physics Letters.

Pei Sung received a Ph.D. degree in Ceramic Engineering, December 1967. Thesis title: "Equilibrium Solubility and Diffusivity of Helium in Single-Crystal Uranium Dioxide."

MÖSSBAUER STUDIES

J. G. Dash
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Edward A. Stern
Professor, Department of Physics

Robert L. Ingalls
Assistant Professor, Department of Physics

Duane P. Johnson
Predoctoral Research Associate, Department of Physics (June 16 to August 31)
Ph.D. Thesis Research

Gerald A. Erickson
Predoctoral Research Associate, Department of Physics (June 16 to December 15)
Ph.D. Thesis Research

James A. Jackobs
Research Assistant, Department of Physics (June 1 to August 31)
M.S. Thesis Research

John R. Nett
Teaching Assistant, Department of Physics
Ph.D. Thesis Research

C. D. West
Teaching Assistant, Department of Physics
Ph.D. Thesis Research

The overall objective is the study of atomic bonding and lattice dynamics in certain ceramic and ceramic-related systems, by means of the Mössbauer effect. Specific portions include: study of low temperature anharmonicity in ferric and ferrous compounds, study of charge state relaxation following beta-decay, high pressure studies, and electron density distributions (charging) in Ag-Sn alloys.

Several new sources have been prepared for continuing experiments on anharmonicity and for the study of charge relaxation. Preliminary work on the charging study indicates that the experimental design will have adequate sensitivity for the Ag-Sn alloy system.

An experimental study of force constants and anharmonicity in FeF_2 and FeCl_2 has been completed and a manuscript is being prepared for publication. A theoretical analysis of the effects of anharmonicity on the Mössbauer spectrum has been submitted to The Physical Review. A note describing a Mössbauer cryostat has been accepted by Review of Scientific Instruments.

Duane P. Johnson received a Ph.D. in Physics in September 1967. Thesis title: "Mössbauer Effect of Fe^{57} in FeF_2 and FeCl_2 ."

EFFECTS OF RADIATION UPON CERAMIC MATERIALS

James I. Mueller
Professor, Ceramic Engineering

The optical properties of many ceramic materials change with prolonged exposure to solar radiation in a vacuum. An understanding of the mechanism of this process is sought in terms of 1) mechanical imperfections in the crystal; 2) impurity concentrations and the interaction of these impurities with crystal imperfections; and 3), thermal and mechanical history of the specimen.

Ultra-Violet Photolysis Study

William M. Ziniker
Senior Research Associate, Ceramic Engineering

Jack K. Merrow
Predoctoral Associate, Ceramic Engineering (June 16 to December 15)
Ph.D. Thesis Research

Lakshmi Annapoorni
Research Assistant, Ceramic Engineering (June 16 to December 15)
M.S. Thesis Research

This project will implement the study of the effects of ultra-violet radiation upon ceramic materials through measurements of optical absorbance, reflectance, photoluminescence, and thermoluminescence. Present work is aimed at the measurement of spectral thermoluminescence of MgO as a function of impurity concentrations and heat treatment.

No meaningful data has yet been gathered, but preliminary measurements indicated the need for more carefully constructed optical components for work in the ultra-violet portion of the spectrum. In addition, the sample holder has been re-designed so as to be amendable to measurements of absorbance, reflectance, and photoluminescence, as well as thermoluminescence. All major components (cryostat, vacuum system, monochrometers, and electronic detection equipment) are now in place, and the apparatus will soon be ready for calibration experiments.

A major part of the work in the future will undoubtedly center on sample preparation. Single crystal, powder, sintered, and flume-sprayed samples of various materials will be investigated. Simultaneous measurements of photoconductivity, which can be performed with the present apparatus without major modification, and parallel electron spin resonance studies will probably also be useful in understanding the electronic processes which take place during radiation damage.

FERROELECTRIC MATERIALS STUDY

Robert J. Campbell, Jr.
Assistant Professor, Ceramic Engineering

The objective of these studies is the development of an explanation of the mechanism of energy storage in ferroelectric materials, resulting from displacement of atoms in the crystal lattice.

Time Dependent Properties

Tracy L. Scott
Research Assistant, Ceramic Engineering (June 16 to September 15)
M.S. Thesis Research

Earlier work on barium titanate demonstrated the influence of grain size on the change of dielectric constant with time.

Barium titanyl oxalate was pyrolyzed to BaTiO_3 of 0.1μ grain size. Samples hot pressed at 9200 psi and 1175°C for sixty minutes yielded polycrystalline bodies of 99 percent density and 0.3μ grain size.

Samples of this material were annealed for one hour each at 1200, 1250, 1300, 1350 and 1400°C . The resulting variation of grain size (0.3 to $+100\mu$) was correlated against the change of dielectric constant with time. The motion of domain walls inside the crystals is sensitive to the size of the grain. Aging rates are lower in finer grained material.

Tracy L. Scott received an M.S. in Ceramic Engineering, December 1967. Thesis title: "Effect of Microstructure on the Aging of Hot Pressed Barium Titanate."

Electrical Conduction in Glass

James W. Vogan (Unsupported)
Part-time Graduate Student, Ceramic Engineering
M.S. Thesis Research

The study of electrochemical potential of iron in glasses has been limited by materials to studies of very low oxygen pressures in the Fe, Al, Si, O system. Molybdenum electrodes protected by an argon atmosphere are being used.

The electrical conduction shows a change of slope at a temperature corresponding to the equilibrium melting temperature of FeO , Al_2O_3 , SiO_2 at very low O_2 pressures. No crystalline phases were detected by x-ray analysis.

Ferroelectric Structure

Richard E. Deno (Office of Engineering Research)
Research Assistant, Ceramic Engineering
M.S. Thesis Research

The correlation of polarization with mechanical deformation of ferroelectric polycrystalline materials has reached an apparatus construction stage.

A strain cage capable of producing compressive stress while subjecting the sample to vibratory stress has been completed.

The study of the effect of mechanical deformation of ferroelectrics during polarization has shown that there is an increase in polarization under the conditions stated above.

Samples of a calcium, cobalt stabilized BaTiO_3 were subjected to pressure and vibration normal to the faces electroded for polarization while a DC field was applied. These showed an increased remanent polarization over samples not vibrated during polarization.

Richard E. Deno received an M.S. in Ceramic Engineering, December 1967.
Thesis title: " BaTiO_3 Polarization, Physical Acoustic Effects."

DEFECT PROPERTIES OF IONIC AND CERAMIC CRYSTALS

Thomas G. Stoebe
Assistant Professor, Metallurgical Engineering

This investigation concerns the growth of single crystals, the evaluation of their defect structure and the determination of the effects of different defect structures on mechanical properties.

Mechanical Properties of LiF

Hira L. Fotedar
Research Assistant, Metallurgical Engineering (September 16 to December 15)
M.S. Thesis Research

The mechanical properties of pure LiF single crystals have been investigated to determine yield stress and work hardening rates. Stress relaxation experiments have indicated serrated relaxation curves, yet to be explained. Single crystals containing varying amounts of impurities are to be grown to investigate the impurity dependence of the mechanical properties.

Mechanical Properties of MgO

M. Srinivasan

Research Assistant, Metallurgical Engineering (September 16 to December 15)

M.S. Thesis Research

A literature survey concerning the feasibility of MgO single crystal growth has been completed, and plans are underway to develop the plasma Verneuil technique for this purpose. Concurrently, a literature survey is being conducted concerning mechanical properties of MgO and a deformation apparatus is being designed.

Ionic Conductivity Studies

Richard Trantow

Undergraduate Aide, Metallurgical Engineering

B.S. Thesis Research

Ionic conductivity provides an excellent technique for obtaining information on the defect structure of ionic crystals. The experimental setup for such measurements is nearly complete and the associated electronics for both A.C. and D.C. conductivity determinations is on hand. Experiments are to be conducted in single crystals of LiF and KI containing various impurities.

SURFACE PHENOMENA

Many properties of ceramic materials are governed by the character of the grain boundaries of the polycrystalline composite. This research area was established to obtain fundamental information regarding the chemistry and physics of the surfaces of ceramic materials.

ALUMINUM OXIDE BICRYSTALS

William D. Scott
Assistant Professor, Ceramic Engineering

The purpose of this research is to study the properties of grain boundaries in macroscopic bicrystals of aluminum oxide of controlled misorientation.

Mechanical Properties of Aluminum Oxide Bicrystals

Henry Y. B. Mar
Predoctoral Associate, Ceramic Engineering (June 16 to December 15)
Ph.D. Thesis Research

The purpose of this project is to produce aluminum oxide bicrystals with controlled misorientation and to study the fractures which are produced from internal stresses caused by thermal expansion mismatch in certain bicrystal configurations.

Pressure sintered bicrystals have been fabricated with various misorientations to produce thermal expansion mismatch ranging from zero to the maximum possible in aluminum oxide. Spontaneous fractures originating in the grain boundary and extending into the crystals on either side have been observed in specimens with substantial expansion mismatch. A finite-element stress analysis model has been developed to calculate with the aid of a computer, the stress concentrations which develop at discontinuities such as pores and free edges. The model predicts very high stresses which approach the theoretical strength of alumina. Additional bicrystal specimens are being fabricated to obtain a more direct comparison between the actual and the model bicrystals.

Internal stresses from thermal expansion mismatch are not usually considered to be significant in aluminum oxide. This study should provide information on the true magnitude of internal stresses as they related to fracture initiation in alumina.

Raymond L. Bertolotti
 Research Assistant, Ceramic Engineering (September 25 to December 15)
 Ph.D. Thesis Research

The purpose of this project is to study grain boundary sliding in aluminum oxide by subjecting grain boundaries in aluminum oxide bicrystals to pure shear loading at elevated temperatures.

One of the primary mechanisms of polycrystalline deformation at high temperature is thought to be grain boundary sliding. The kinetics of this process and the relationship of boundary sliding to dislocation motion in the crystals adjacent to the boundary will be investigated in pressure sintered bicrystals of controlled misorientation.

Pore Growth and Pore Removal in Grain Boundaries of Aluminum Oxide

William D. Soctt
 Assistant Professor, Ceramic Engineering

The purpose of this project is to study the formation and subsequent removal of pores located on grain boundaries in aluminum oxide bicrystals, and to relate this pore behavior to sintering and diffusion in aluminum oxide.

Pore growth and the development of continuous channel pore structures are being studied in bicrystals and polycrystals of aluminum oxide. Selected areas of bicrystal boundaries are being photographed and the pore structure followed as a function of annealing time at 1850°C. The anneal time is now at 130 hours and presently is being carried out in 48-hour increments.

Impurity Diffusion in MgO Under the Influence of an Electric Field

Chester A. Hinman
 Predoctoral Associate, Ceramic Engineering (June 16 to December 15)
 Ph.D. Thesis Research

The purpose of this project is to investigate the diffusion of nickel in MgO at high temperature and in an electric field. By using the microprobe to measure the drift of the diffusion profile in a sandwich diffusion couple, one can obtain, with the help of other bulk diffusion data, the mobility and effective change of the nickel ions. Information can also be obtained on the diffusion mechanism.

Several diffusion runs on sandwich MgO-NiO-MgO couples have been carried out at 1450°C and 50 to 200 volt cm^{-1} field. The resistivity decreases with time and is non-ohmic and anomalous movement of the nickel layer was observed. At the present time, the conductivity of pure MgO crystals is being studied to establish basic conductivity mechanisms before impurity diffusion studies are continued.

Interfacial Energies of Aluminum Oxide Bicrystals

James F. Shackelford

Research Assistant, Ceramic Engineering (June 16 to September 15)

M.S. Thesis Research

The purpose of this project is to determine the relative interfacial grain boundary energies in aluminum oxide by measuring the profile of thermally etched boundaries.

The relative interfacial energy has been measured for a series of symmetric tilt boundaries with misorientations from 0 to 180°. A steeply rising energy at low angles and a broad plateau of constant interfacial energy were observed. A calculation of boundary energy based on the theoretical model of J. C. M. Li gave good agreement with experimental results. Surface diffusion coefficients were determined from the kinetics of thermal grooving. The results substantiated data of previous investigators on small angle boundaries in nominal single crystal alumina.

A paper entitled "Relative Energies of Tilt Boundaries in Aluminum Oxide," was presented at the American Ceramic Society, Pacific Coast Regional Meeting, November 1967, and is being submitted for publication in the Journal of the American Ceramic Society.

James F. Shackelford received an M.S. in Ceramic Engineering, August 1967. Thesis title: "Relative Energies of [1010] Tilt Boundaries in Aluminum Oxide."

The Effect of MgO Impurity on Relative Interfacial Energy in Alumina

Michael Matson (Unsupported)

Part-time Graduate Student, Ceramic Engineering

M.S. Thesis Research

The purpose of this project is to measure the effect of the presence of MgO on the grain boundary energy of alumina and to correlate this effect with current theories of sintering in alumina.

Bicrystals have been fabricated with and without MgO doping in the boundary. The boundaries have been thermally etched in air and measurements of thermal groove root angles are being made.

ELECTROMAGNETIC FIELDS FROM DIELECTRIC LOADED APERTURES

H. Myron Swarm
Professor, Electrical Engineering

Irene C. Peden
Associate Professor, Electrical Engineering

James C. Rogers
Predoctoral Associate, Electrical Engineering (June 16 to July 15)
Ph.D. Thesis Research

The purpose of this project is to define methods of electromagnetic horn pattern shaping which are suitable for ceramic materials.

This work will supplement previous experimental and theoretical work which resulted in master of science thesis entitled "Dielectric Loading of an Electromagnetic Horn."

This effort has been concerned with easier methods of obtaining a desired dielectric variation across the horn aperture and further work on the effects of the shape of the dielectric loaded aperture upon the radiation pattern. Experimental work to determine the thickness of the loading material required for satisfactory pattern shaping has been completed.

SURFACE DIFFUSION

Jerry E. Turnbaugh
Assistant Professor, Ceramic Engineering

Edward H. Randklev
Predoctoral Associate, Ceramic Engineering (June 16 to December 15)
Ph.D. Thesis Research

The purpose of the project is to measure surface diffusion coefficients in order to obtain information upon the structure and chemical nature of the surface of ceramic materials.

Construction of apparatus and survey of literature are continuing. Preliminary calculations based on literature data indicate that the system $\text{Al}_2\text{O}_3\text{-Cr}_2\text{O}_3$ is experimentally suitable.

PROCESSING

Research in this area is intended to gain information relative to the effect of processing variables upon the micro- and macro-structure of ceramic materials and upon their resultant properties.

CERAMIC PROCESSING

O. J. Whittemore, Jr.
Associate Professor, Ceramic Engineering

Initial Stages of Sintering

J. Joseph Sipe
Predoctoral Associate, Ceramic Engineering (June 16 to December 15)
Ph.D. Thesis Research

Ralph Hawks, Jr.
Undergraduate Aide, Ceramic Engineering

The objective of this project is to study the initial stages of sintering where pore growth occurs. This phenomenon has been shown to occur during the sintering of several ceramic materials and it also has been shown that it may occur simultaneously with shrinkage. Auxiliary objectives are to determine whether pore growth occurs generally and its controlling mechanisms.

Experiments continue on the initial sintering of ferric oxide and include preparation of samples for electron microscopy to confirm the data obtained by mercury porosimetry. Consideration is also being given to wetting angle measurements. A "Sorbet" surface area apparatus has been purchased which should provide data on surface area changes during sintering as an independent confirmation of mercury porosimetry measurements.

Characteristics of Plasma-Sprayed Oxides

The paper entitled "Structural Changes on Reheating Plasma-Sprayed Alumina" by Vere S. Thompson and O. J. Whittemore, Jr. has been reviewed and approved for publication in the Bulletin of the American Ceramic Society.

Characterization and Forming

Douglas J. Calkins

Predoctoral Associate, Ceramic Engineering (June 16 to September 15)

Ph.D. Thesis Research

Daniel Leiser

Predoctoral Associate, Ceramic Engineering (June 16 to December 15)

Ph.D. Thesis Research

The objectives of this project are to study ceramic forming methods and to correlate characterization of particles and agglomerates with forming and subsequent product properties. Present activities are being devoted to the study of compaction.

A particle discriminator was constructed which rejects elliptical glass particles from samples of glass spheres. After careful rescreening to exact sizes, the discriminator is being used to prepare uniform material which will be compacted under controlled pressure and rate into compaction cells. Pore size distributions will then be measured together with particle size analysis after compaction. From these tests, it is hoped to derive a more nearly exact expression for the compaction process.

Compaction studies have been made at various compaction rates of single sizes of fused magnesia (cube shaped), fused mullite (rectangular prism shaped), fused alumina (irregular spherically shaped), and glass spheres. Factors have been computed fitting these data to a statistical equation assuming the two processes to be considered are rearrangement and fracture.

A paper entitled "Influence of Rate and Particle Size on Particle Compaction" by D. B. Leiser and O. J. Whittemore, Jr. was presented at the Pacific Coast Regional Meeting of the American Ceramic Society, San Francisco, California, November 2, 1967.

Development of Electrical Porcelain from Pacific Northwest Materials

Donald Wakekamper (Edward Orton Jr. Ceramic Foundation Fellowship)

Research Assistant, Ceramic Engineering

M.S. Thesis Research

The objective of this project is to develop electrical porcelains utilizing ceramic raw materials from the Pacific Northwest. Properties of the raw materials will be related with the resultant properties of the porcelains.

Lake Wenatchee, Washington feldspar and Lane Mt., Washington silica fines were milled and substituted in a typical porcelain body together with Ione, California kaolin. Various "splits" of the Lane Mt. silica in the micron range were also substituted to note the effect of silica sizing on properties. First trials had satisfactory electrical properties but were somewhat porous.

MECHANICAL AND PHYSICAL PROPERTIES OF FLAME SPRAYED ZrC COATING AND SUBSTRATE

Colin J. Sandwith
Assistant Professor, Mechanical Engineering

James D. Danberg
Research Assistant, Mechanical Engineering (September 25 to December 15)
M.S. Thesis Research

This investigation is to determine microhardness and bond strengths and to design and apply a new test of mechanical properties of ZrC plasma flame-sprayed coatings.

The literature review indicates that current bond strength test variables quantify and define only ultimate strengths. This limitation demands the use of statistics and a multitude of specimens to predict trends in brittle materials. To avoid this it is planned to use an infrared or ultrasonic nondestructive test to examine specimens before and after destructive testing. This procedure, supplemented with metallography, should permit analysis and description of the failure, rather than obtaining only the strength value of each specimen. The differential equations which describe the most promising infrared thermography test have been derived. It has only recently been established that instruments and procedures have been commercially developed for a similar test.

Zr powder for flame spraying has been ordered, tensile bond strength test specimens have been fabricated, and three different materials, W_4C , Al_2O_3 , and nickel aluminide, have been flame sprayed for comparison purposes.

EFFECT OF LANTHANUM DOPING UPON BARIUM TITANATE

James I. Mueller
Professor, Ceramic Engineering

Ronald P. Burley (National Lead Co. Fellowship)
Research Fellow, Ceramic Engineering
M.S. Thesis Research

This investigation was initiated to determine the effects of processing parameters such as type of lanthanum additive, firing temperature and furnace atmosphere upon the micro- and macro-properties of barium titanate.

The work was completed during the report period and all data supported the conclusion that the lanthanum dopant forms a solid solution with barium titanate. Indications were that A-site vacancies were formed and no evidence was found of second phase formation. It appeared that oxidation and reduction of the solid solution material occurred readily and was reversible.

Mr. Burley completed the M.S. in Ceramic Engineering, August 1967. Thesis title: "Microstructure Effects on Semiconductive Barium Titanate Ceramics."

CHARACTERIZATION OF FORSTERITE PORCELAINS

James I. Mueller
Professor, Ceramic Engineering

Roger Hanson (Tektronix Fellowship)
Research Fellow, Ceramic Engineering
M.S. Thesis Research

This research has just been initiated to ascertain the effects of various processing parameters upon the nature and properties of forsterite porcelains. A literature review has been completed and experimental work is being outlined.

APPENDIX A-1

Distribution of Projects Within the University According to Research Areas

<u>Academic Department</u>	<u>Number of Projects</u>	<u>Zr-O-C</u>	<u>Solid State</u>	<u>Surface</u>	<u>Process</u>
Chemistry	2	1	1	-	-
Ceramic Engineering	15	4	3	6	2
Electrical Engineering	2	-	1	1	-
Mechanical Engineering	1	-	-	-	1
Metallurgical Engineering	5	3	2	-	-
Physics	1	-	1	-	-
	<u>26</u>	<u>8</u>	<u>8</u>	<u>7</u>	<u>3</u>
TOTAL	26	8	8	7	3

APPENDIX A-2

Number of Students and Faculty Involved in Research Supported by Grant Funds

<u>Academic Department</u>	<u>Number of Projects</u>	<u>Faculty</u>	<u>Research Faculty</u>	<u>Under Grads</u>	<u>MS</u>	<u>Ph.D.</u>	<u>Total Grads</u>
Chemistry	2	2	-	-	-	2	2
Ceramic Engineering	15	5	2	1	4	12	16
Electrical Engineering	2	3	-	-	-	2	2
Mechanical Engineering	1	1	-	-	1	-	1
Metallurgical Engineering	5	4	-	1	4	1	5
Physics	1	3	-	-	1	2	3
	<u>26</u>	<u>18</u>	<u>2</u>	<u>2</u>	<u>10</u>	<u>19</u>	<u>29</u>
TOTAL	26	18	2	2	10	19	29

APPENDIX B

Ceramic Materials Research Seminars

"Ceramic-Reinforced Composites"

Mr. S. W. Bradstreet, Technical Consultant, Dayton, Ohio

"The Strength of Ni-Base Superalloys"

Dr. S. M. Copley, Advanced Materials Research and Development Laboratory, Pratt and Whitney Aircraft, Middletown, Connecticut

"Mechanical Properties of Alumina"

Dr. Arthur H. Heuer, Case Institute of Technology, Cleveland, Ohio

"Optical and ESR Studies of Trapped Electrons in Alkaline Earth Oxides"

Dr. James C. Kemp, Associate Professor, Department of Physics, University of Oregon, Eugene, Oregon

"Interatomic Distance from X-ray Absorption Fine Structure"

Mr. F. Lytel, Boeing Scientific Research Lab

"Thermal Expansion Anisotropy Induced Fracture in Alumina Bicrystals"

Mr. Henry Y. B. Mar, Predoctoral Research Associate, Ceramic Engineering

"Electron Irradiation Strengthening in Metals and Alloys"

Dr. M. Meshii, Department of Materials Science, The Technological Institute, Northwestern University

"Electronic Band Structure and Oxygen Potential in the System Zr-C-O"

Mr. Alan D. Miller, Predoctoral Associate, Ceramic Engineering

"Review of Ceramic Materials Research Program"

Dr. James I. Mueller, Professor of Ceramic Engineering

"Equilibrium Solubility of Helium in Single-Crystal Uranium Dioxide"

Mr. Pei Sung, Predoctoral Associate, Ceramic Engineering

"Mechanical Tests of Flame Sprayed Coatings"

Dr. Colin J. Sandwith, Assistant Professor of Mechanical Engineering

"Calorimetric Investigation of ZrC"

Mr. Hugo W. Schimmelbusch, Research Assistant, Metallurgical Engineering

"F-F¹ Photoconversion Experiments in Additively Colored CaO"

Dr. William M. Ziniker, Senior Research Associate, Ceramic Engineering

APPENDIX C

Theses Published

"Mössbauer Effect of Fe^{57} in FeF_2 and FeCl_2 "
(Duane P. Johnson) Ph.D., Department of Physics

"Prediction of Isothermal Ternary Phase Diagrams Using Binary Thermodynamic Data"
(Dong Nyung Lee) M.S., Metallurgical Engineering

"Electronic Band Structure and Oxygen Potential in the Zr-C-O System"
(Alan D. Miller) Ph.D., Ceramic Engineering

"Effect of Microstructure on the Aging of Hot-Pressed Barium Titanate"
(Tracy L. Scott) M.S., Ceramic Engineering

"Relative Energies of $[\bar{1}010]$ Tilt Boundaries in Alumina"
(James F. Shackelford) M.S., Ceramic Engineering

"Equilibrium Solubility and Diffusivity of Helium in Single-Crystal Uranium Dioxide" (Pei Sung) Ph.D., Ceramic Engineering

APPENDIX D

Papers Published:

"180° Domain Formation in Ferroelectrics with Shorted Electrodes," John L. Bjorkstam and Richard E. Oettel, Physical Review, 159(2), pp. 427-430, (10 July 1967).

"Optical Evidence that the Low-Temperature Phase of Rochelle Salt is Antipolar," Richard E. Oettel and John L. Bjorkstam, Bulletin of the American Physical Society, 12(6), p. 902 (1967).

Papers Accepted for Publication:

"Calculation of the Temperature-Dependent Shear Modulus of UO_2 ," J. E. Turnbaugh and Pei Sung, Journal of Nuclear Materials.

"Calculation of Diffusivity and Solubility with Error Analysis for Diffusion in a Sphere," J. E. Turnbaugh and Pei Sung, Journal of Applied Physics Letters.

"Structural Changes on Reheating Plasma-Sprayed Alumina," Vere S. Thompson and O. J. Whittemore, Jr., Bulletin of the American Ceramic Society.

Papers Submitted for Publication:

"Relative Energies of Tilt Boundaries in Aluminum Oxide," James F. Shackelford and W. D. Scott, Journal of the American Ceramic Society.

Papers Presented:

"Influence of Rate and Particle Size on Particle Compaction," D. B. Leiser and O. J. Whittemore, Jr., Pacific Coast Regional Meeting of the American Ceramic Society, San Francisco, California, November 2, 1967.

"Ceramic Materials Research at the University of Washington," J. I. Mueller, O. J. Whittemore, Jr., W. D. Scott and A. D. Miller, 13th Meeting of the Refractory Composites Working Group, Seattle, Washington, July 19, 1967.

"Relative Energies of Tilt Boundaries in Aluminum Oxide," James F. Shackelford and W. D. Scott, Pacific Coast Regional Meeting of the American Ceramic Society, San Francisco, California, November 1967.

"Ceramic Materials Research at the University of Washington," J. I. Mueller, Annual Meeting of the Pacific Northwest Ceramic Association, Spokane, Washington, October 1967.

APPENDIX E

CERAMIC MATERIALS RESEARCH PROGRAM REVIEW
November 6-7, 1967

The success of the program review in November 1966, to which representatives of government and industrial research organizations were invited, led to a similar type program this year. Invitations were sent to appropriate individuals in all federal agencies and to officials of the Pacific Coast ceramic industry, aerospace industry and non-profit research organizations.

The morning program each day was devoted to 10-15 minute briefings by the faculty research supervisors. During the afternoons, the attendees visited the various faculty members in their laboratories and discussed their research in detail.

Favorable reaction was received relative to this type of presentation with most of the attendees indicating their pleasure in being able to observe and discuss on-going research rather than having to experience the normal delays involved in presentation and publication.

SUMMARY OF ATTENDEES

Visitors	17
Faculty Supervisors	15
University Administrators	3

	Distribution by State				
	<u>Washington</u>	<u>Oregon</u>	<u>California</u>	<u>D. C.</u>	<u>Total</u>
Industry					
Ceramic	1	-	2	-	3
Aerospace	7	-	1	-	8
Other	-	2	-	-	2
Federal Agencies					
NASA	-	-	-	1	1
NBS	-	-	-	1	1
USBM	-	1	-	-	1
Non-Profit Research	<u>1</u>	<u>-</u>	<u>-</u>	<u>-</u>	<u>1</u>
	9	3	3	2	17

APPENDIX F

Number of Advanced Degrees Received by Students Supported by the Program

The following is a tabulation of the number of recipients of graduate degrees by academic discipline who have been fully or partially supported by program funding. The figures do not include students who are currently in residence.

<u>Academic Discipline</u>	<u>M.S. Degrees</u>		<u>Ph.D. Degrees</u>	
	<u>Partial Support</u>	<u>Full Support</u>	<u>Partial Support</u>	<u>Full Support</u>
Atmospheric Sciences	-	1	-	-
Ceramic Engineering	5	12	1	2
Chemistry	-	-	2	-
Metallurgical Engineering	-	4	2	1
Physics	-	-	-	2
	<hr/>	<hr/>	<hr/>	<hr/>
TOTAL	5	17	5	5

APPENDIX G

Distribution

Mr. Francis Smith
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